Simons

ANL-7807

ANL-7807

SURVEY OF THERMONUCLEAR-REACTOR PARAMETERS

P. J. Persiani, W. C. Lipinski,
and A. J. Hatch

U of C-AUA-USAEC

ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

Prepared for the U.S. ATOMIC ENERGY COMMISSION
under Contract W-31-109-Eng-38

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy $3.00; Microfiche $0.95

ANL-7807
Controlled Thermonuclear
Processes

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

SURVEY OF THERMONUCLEAR-REACTOR PARAMETERS

by

P. J. Persiani
Applied Physics Division

W. C. Lipinski
Reactor Analysis and Safety Division

A. J. Hatch
Physics Division

October 1972

TABLE OF CONTENTS

	Page
ABSTRACT	5
I. INTRODUCTION	5
II. FORMAT AND TABLE STRUCTURE	6
III. POWER-BALANCE PARAMETERS	7
IV. REACTOR PARAMETERS FOR CLOSED SYSTEMS: TABLE I	8
A. Stellarators	8
B. Tokamaks	9
C. Toroidal Machines	14
D. Toroidal θ-pinch (Scyllac)	15
V. REACTOR PARAMETERS FOR OPEN-ENDED SYSTEMS: TABLE II	16
A. Mirror Machines	16
B. Astron	21
C. Linear θ-pinch (Scylla)	21
VI. REMARKS	22
REFERENCES	23

SURVEY OF THERMONUCLEAR-REACTOR PARAMETERS

by

P. J. Persiani, W. C. Lipinski, and A. J. Hatch

ABSTRACT

This preliminary survey makes available for ready reference some of the important thermonuclear-reactor parameters generated by the variety of concept studies reported in the open literature. Many of the more than 25 studies are essentially partial design concepts, emphasizing specific problem areas involved in developing a fusion power reactor. The term "design" in this report will be applied to all the sets of parameters cited, even though in many cases only a few self-consistent parameters are used to illustrate a limited aspect of the overall design problem. The composite tabulation of these parameters does allow a measure of convenience in scoping the overall effort that has been applied to the general area of feasibility and development of fusion reactors (as distinguished from plasma problems).

The parameters are presented in such a way as to compare the reactor types and to identify major subsystems that have as yet received only minimal attention. Although a comparison of certain selected parameters is indeed an objective of this compilation, an evaluation of each of the systems and/or subsystems is beyond the scope of this report.

It is also intended that the compilation will serve as background material for a subsequent phase of developing a coordinated overall reactor systems-design study. In this manner, an overall systems study would bring into better perspective the many conflicting design constraints and interface problems.

I. INTRODUCTION

Engineering design studies in programmatic planning for the timely development of large complex systems, such as a fusion-reactor plant, are necessary in order to identify and evaluate major problem areas, various technical approaches, and potential methods of solution, and to establish relative priorities in research and development. As an aid in the development of such an overall CTR (controlled thermonuclear research) program plan, the various fusion-reactor concept studies reported in the literature have been surveyed. The purpose of the survey is to make available for ready reference some of the important thermonuclear-reactor parameters generated in the design studies. Many of the more than 25 studies are essentially partial design concepts, emphasizing specific problem areas involved in developing a fusion power reactor. The term "design" in this report will be applied to all the sets of parameters cited, even though in many cases only a few self-consistent parameters are used to illustrate a limited aspect of the overall design problem. The composite tabulation of these parameters allows a measure of convenience in scoping the overall effort that has been applied to the general area of feasibility and development of fusion reactors (as distinguished from plasma problems).

The parameters are presented in such a way as to compare the reactor types and to identify major subsystems that have as yet received only minimal attention. Although a comparison of certain selected parameters is indeed an objective of this compilation, an evaluation of the systems and/or subsystems is beyond the scope of this report.

It is also intended that the compilation will serve as background material for a subsequent phase of developing a coordinated overall reactor systems-design study. In this manner, an overall systems study would bring into better perspective the many conflicting design constraints and interface problems.

II. FORMAT AND TABLE STRUCTURE

The basis used for the selection of material to be included in the tabulation is that the design study be published in open literature and that the partial or subsystem concepts relate to a specific type of fusion reactor.

An attempt is made to present the information for all types of systems in as uniform a manner as is possible. The table is structured into 10 sections which essentially cover the major subsystems of a complete system design. The sections listed are:

1. Power
2. Energy conversion
3. Reactor dimensions
4. Plasma parameters
5. Magnet system
6. Blanket system
7. Primary coolant system
8. Direct-conversion system
9. Fueling system
10. Fuel recovery and by-product removal system

With some modifications, the above sections were found to be consistent in categorizing the basically different fusion-reactor types. The first three sections contain the general descriptive information on the main features of a power-reactor system. The next two sections list the more specific parameters describing the plasma operating conditions and the magnet system needed to attain these conditions. The sections on the Blanket, Primary Coolant, and Direct-conversion Systems list the parameters relating to the power-conversion techniques. The Blanket and Primary Coolant Systems are part of the thermal power-conversion system; the Direct-conversion System includes direct electrical power generation from escaping charged particles and/or from charged particle motion against magnetic fields. The Fueling System section includes parameters relating to the injection subsystem as well as the fuel-cycle balance. The final section, the Fuel Recovery and By-Product Removal System, lists data pertinent to the vacuum-systems throughput and to fuel production.

The compilation is presented in two tables. Table I lists the specifications relating to the closed systems: stellarators, tokamaks, toroidal machines, and θ-pinch. The stellarators and tokamaks are low-β machines ($\beta < 10\%$) and are listed next to each other in the left-hand section of the table. The generally medium-β ($10\% < \beta < 90\%$) toroidal machines are combined, and the high-β ($\beta > 90\%$) θ-pinch machine completes the table of closed-system reactors.

Table II lists the parameters associated with the open-ended systems: mirrors, astrons, θ-pinch, continuous-flow pinch, and long-cusp machines. In a similar grouping as in Table I, the generally low-β mirror and astron machines are listed on the left-hand section of the table, with the high-β machines completing Table II.

III. POWER-BALANCE PARAMETERS

In establishing the compilation for comparison studies, we found that the two important power-balance parameters, (1) Q (ratio of output to input power), and (2) ϵ (fractional circulating power), were defined differently in several studies, even within a class of reactor systems.[1] Referring to the power-flow diagram (Fig. 1), the definition adopted for this survey is that the Q factor of a fusion power reactor, independent of subsystems, be defined as the ratio of the total reactor power output P_o (across interface B) to the total power input P_i (across interface A),

$$Q = \frac{P_o}{P_i} = \frac{P_f + P_i}{P_i}, \tag{1}$$

where P_f is the fusion power generated in the power-source subsystem, and P_i is the power input to the power-source subsystem.

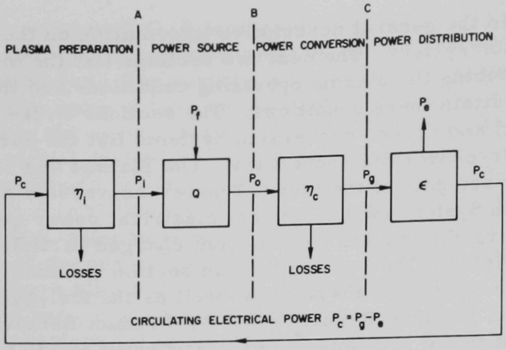

Fig. 1

Basic Power-flow Diagram.
ANL Neg. No. 116-1080.

The input power to the power-source subsystem of a fusion reactor is the product of the overall plasma-preparation efficiency η_i and the circulating power P_c into the plasma-preparation subsystem. The circulating power is the difference between P_g, the gross electrical power output from the power-conversion subsystem (across interface C), and P_e, the net electrical power output for distribution,

$$P_c = P_g - P_e. \tag{2}$$

The fractional circulating power ϵ is defined as

$$\epsilon = \frac{P_c}{P_g}. \tag{3}$$

The definitions of Q and ϵ as suggested above and in Ref. 1 are most general and are applicable to complex systems involving a combination of thermal and direct power-conversion techniques. On this basis, the Q values and ϵ can provide a measure of performance for the comparison of fundamentally different approaches to a fusion-power-reactor system (closed, open-ended, or fusion by laser ignition). Since not all studies made available the assumed injection efficiency η_i, the compilation was made for a slightly altered but related quantity $Q' = \eta_i Q$.

IV. REACTOR PARAMETERS FOR CLOSED SYSTEMS: TABLE I

A. Stellarators

1. The first preliminary design of a practical fusion reactor was carried out in 1954 by Spitzer et al.[2] Of all the papers reviewed for the current survey, this early effort was found to be the most complete design study of a fusion reactor.

The primary purposes of the study by Spitzer et al. were to explore problems associated with full-scale power systems and to identify those areas requiring further research and development. Their preliminary design approach was based on two assumptions: (a) Confinement of charged particles would be accomplished by magnetic fields, and (b) a fuel mixture of 50% deuterium and 50% tritium would be most practical because of the high D-T reaction cross-section values.

Spitzer et al. considered three net power-producing operating conditions with maximum values of the confining magnetic field strength, B, equal to 50, 75, and 100 kG. The lower limit was based on the consideration that magnetic fields less than 50 kG would yield an unfavorable power balance, the Q' of the 50-kG system being approximately 6. The upper limit of 100 kG, which yielded a Q' value of 23, was based on the consideration that larger fields would involve severe problems of structural strength and heat transfer. In the present survey we cite their intermediate case of the 75-kG system.

The thoroughness of this design is evident from the fact that design figures are obtained for nearly every category included in the table. No other design approaches it in this respect.

2. Gibson[3] presents permissible parameters for economic closed-system tokamak and stellarator reactors. Theoretical estimates are given for the maximum beta for which toroidal equilibria can exist. The restrictions on the parameters of a net-power-producing reactor are examined by considering the actual average ratio of plasma to magnetic pressure achieved in a reactor system as a departure from the maximum theoretical equilibrium estimates. Parametric curves are presented for tokamaks and stellarators showing total reactor power and aspect ratio as a function of a normalized β for several field strengths. Gibson summarizes the important parameters for selected total power ratings for two tokamaks and three stellarators. The medium-power-rating case, 3200 MWe for the stellarator system is presented in column 2, Table I. The higher-power system, 15,000 MWe, uses a maximum field strength of 200 kG and the same average $\beta = 0.03$ as given for the medium-power case. The low-power case, 1900 MWe, relates to a maximum field at the windings of 100 kG and to an average $\beta = 0.10$. The corresponding calculated power fluxes at the wall are 13 and 8 MW/m^2 for the high- and low-power systems, respectively.

B. Tokamaks

1. Golovin et al.[4] investigate some of the necessary parameters for a net power-producing fusion reactor of the tokamak type. The mode of operation is pulsing the magnetic field to an amplitude of 50 kG in order to maintain a plasma current over a 100-sec pulse. The investigators confine their study to the plasma-related design criteria, adopting a maximum

TABLE I REACTOR PARAMETERS FOR CLOSED SYSTEMS

			Stellarators		Tokamaks					Toroidal Machines					θ-Pinch
			Spitzer et al.[2]	Gibson[3]	Golovin et al.[4]	Carruthers et al.[5,6] α-Heating	Carruthers et al.[5,6] Injection	Butt[8] Simple Model	Gibson[3]	Mills[9]	Förster & Schneider[10]	Butt[8] Simple Model	James, Newton, Bodin[11,12] Resistive[b]	James, Newton, Bodin[11,12] Supercond[b]	Burnett & Ellis[13]
POWER															
Reactor Output Power	P	MWt	17300		5000	5000	5000	6000		5910	5000[c]	6000	2750 Pk.	7500 Pk.	3380
Gross Electrical Power	P_g	MWe	6000	3200		2300[a]	2300[a]		1650	2010			1170	3220	1350
Net Electrical Power	P_e	MWe	4680			2070	2070			1950	2318		803	2850	
Station Efficiency	$\eta_s = P_e/P$		0.270[a]			0.42	0.42			0.33	0.468		0.292	0.380	
Fractional Circulating Power	$\epsilon = (P_g-P_e)/P_g$		0.22[a]			~0.10[a]	~0.10			0.03		<0.10	0.313	0.115	
$Q' = \frac{\text{Reactor Output Power}}{\text{Circulating Power}}$	$Q' = P/(P_g-P_e)$		13[a]			25[a]	25[a]			98[a]			75[a]	20[a]	
Fusion Pulse Power	P_p	MWt											3350	9100	67,600[a]
Pulse Width	t_w	sec											10	10	0.050
Pulse Period	t_p	sec											11	11	1
ENERGY CONVERSION															
Fusion Reaction			D(T, n) ^{4}He	D(T, n) ^{4}He	D(T, n) ^{4}He	D(T, n) ^{4}He	D(T, n) ^{4}He	D(T, n) ^{4}He	D(T, n) ^{4}He	D(T, n) ^{4}He		D(T, n) ^{4}He			D(T, n) ^{4}He
Plasma Formation & Heating Input Power		MWe	Ohmic		Ohmic	Ohmic	Ohmic	Ohmic				Ohmic			Shock & Compression
Auxiliary Plasma Heating Input Power		MWe	X				X								X
Alpha Heating Power		MWt				X		X		X		X			X
Thermal Conversion Blanket Output Power[c]		MWe	X	X		X	X	X	X	X		X			X
Charged Particle Direct Conversion Power		MWe													
Plasma-Magnet Field Direct Conversion Power		MWe													
Power Conversion System Type			Steam: 900° F, 850 psi			Steam	Steam				Closed He cycle gas turbine				
REACTOR DIMENSIONS															
Torus Major Radius	R	m	7.27	7	5.2	5.5	5.5	5.25	7.0	12.70	6.83	3.5[a]	6.5	10	57
Vacuum Wall Radius	r_w	m	0.66[d]		1.86	1.75	1.75	1.75		1.2[a]	2.0	1.75	1.0	1.75	0.2
Blanket Outer Radius	r_b	m	1.28		3.06	3.00[g]	3.00[g]	3.00		2.4	3.7	3.0	1.8	3.0	
Magnet Coil Outer Radius	r_m	m	2.14	4.75	3.85	3.50	3.50		3.45	2.6	3.9		2.1	3.5	
Axial Length[e]	ℓ	m	165[f]												
Overall Dimensions[e]	w; h; l;	m	3.35; 3.35; 100												
PLASMA PARAMETERS															
Composition (Initial)[h]			D-T	D-T	D-T	D-T	D-T	D-T	D-T	D-T	D-T	D-T	D-T	D-T	D-T
Ion Density (Initial)	n	cm^{-3}	$1.95(10^{15})$		$3(10^{14})$	$2.8(10^{14})$	$4(10^{14})$	$4(10^{14})$		$4.9(10^{14})$		$4(10^{14})$	$44(10^{14})$	$3.5(10^{14})$	$1.4(10^{16})$
Particle Confinement Time	τ	sec	0.331		0.7	0.6	3.5	1.5	1			1.0	10	10	0.050
Confinement Time/Bohm Time	α	τ/τ_B		120	370	120	470	90	240	1		270	1000	1000	
Lawson Number	$n\tau$	cm^{-3}sec	$6.46(10^{14})$[a]		$2.1(10^{14})$[a]	$1.7(10^{14})$	$1.4(10^{15})$	$6(10^{14})$		$4.9(10^{14})$[a]		$4(10^{14})$[a]			$5(10^{14})$
Ion Temperature	T_i	keV	10	20	15	20	13	20	20	10		20	20	20	10.9
Electron Temperature	T_e	keV	10	20	15	20	13	20	20	13.5		20			14.0
Stability Margin	q				1	1.35		1.3	≥3			0.20			
Plasma Pressure/Magnetic Pressure															
Total	β		0.24-0.75	0.3	0.3[i]	0.075	>0.043	0.02	0.045	0.12		0.375	0.4	0.4	~1.0
Poloidal	β_p				3			0.33				0.33			
Toroidal	β_t														
Plasma Current	I	MA	0.182			8.7		28				28	17	25	
Effective Resistance	R_i	$\mu\Omega$	207										2.1	3.2	
Poloidal Magnetic Field	B_p	kG			11.4								56	50	
Major Radius	R	m		7	5.2	5.50	5.50	5.25[a]	7.0	12.7	6.83	3.5[a]	6.5	10.0	57
Minor Radius	a	m		1.75	1.5	1.25	1.25	1.50	1.75	1.0[a]		1.0	0.60	1.0	0.083
Aspect Ratio	$A = R/a$			4	3.5	4.4	4.4	3.5	4	12.7[a]		3.5	11	10	~700
Volume	V_p	liter	$1.92(10^5)$	$4.2(10^5)$[a]	$223(10^3)$	$170(10^3)$	$170(10^3)$	$223(10^3)$[a]	$425(10^3)$	$2.5(10^5)$		$6.9(10^4)$[a]	$46.4(10^3)$	$198(10^3)$	7800
Fusion Power Density	P_f	kWt/liter	88.6		22.4	29.4	29.4	27[a]		18.6[a]		87[a]	59.2	37.9	433[a]

TABLE I REACTOR PARAMETERS FOR CLOSED SYSTEMS (Contd.)

			Stellarators		Tokamaks					Toroidal Machines						θ-Pinch
			Spitzer et al.[2]	Gibson[3]	Golovin et al.[4]	Carruthers et al.[5, 6]		Butt[8] Simple Model	Gibson[3]	Mills[9]	Förster & Schneider[10]	Butt[8] Simple Model	James, Newton, Bodin[11,12]			Burnett & Ellis[13]
						α-Heating	Injection						Resistive[b]	Supercond[b]		
GNET SYSTEM																
Plasma Confining Magnet Field Coil																
Class (Material; Oper. Temp, °C)			Cu; 80°C		Supercond.	Supercond.	Supercond.	Supercond.		Supercond.	Supercond.	Supercond.	Cu ; 250° C	Supercond.		Cu & Supercond
Toroidal Axial Field (r = 0)	B_o	kG		100	40			175	70	65		60				110
Maximum Toroidal Field	B_m	kG		200	100	100	100		110							
Confining Magnetic Field	B_c	kG														
Field in Curved Section at Wall		kG	75													
Field in Straight Section at Wall		kG	42.4													
Rise Time of Magnetic Field	t_r	sec						0.01 to 0.1				0.01 to 0.1	0.5	0.5		
Inside Radius	r_i	m	1.28		3.06	3.00	3.00	3.0		2.4	3.3	3.0	1.8	3.0		
Outside Radius	r_o	m	2.14	4.75	3.85	3.50	3.50		3.45	2.6	3.8		2.1	3.5		
Total Magnetic Power Required	P_m	MW	1300													
Ohmic Heating Transformer																
Primary																
Type of Core													IRON	IRON	AIR	
Core Area													51	113	133	
Magnetizing Current	I_m	MA											0	0	250	
Magnetizing Inductance	L_m	μH											∞	∞	15.1	
Leakage Inductance	L_c	μH											2.34[j]	3.56[j]	3.56[j]	
Inductive Flux	Q_L	Webers											199	444	444	
Resistive Flux	Q_R	Webers											27	54	54	
Pulsed Power Supply Cont. Rating		MW											2100[k]	7200[k]	12800[k]	
Secondary (Plasma)																
Plasma Current	I	MA	0.182[l]			8.7		28				28	17	25	25	
Effective Resistance	R_i	μΩ	207										2.1[m]	3.2[m]	3.2[m]	
Classical Resistance	R_c	nΩ											11.9	7.1	7.1	
Inductance	L_p	μH	21										11.7	17.8	17.8	
Poloidal Field	B_p	kG			11.4[n]								56	50	50	
BLANKET SYSTEM																
Vacuum Wall Loading[p]	P_w	MW/m^2	27.8	13	13	13	13	16.50[o]	7.00	6.18	10	25[o]	13 (Peak)	13 (Peak)		6.09
Divertor Wall Loading	P_d	MW/m^2	0.585[q]													
Energy Deposition		MW/m^2				2.50	2.50									
Materials:																
Vacuum Wall						Mo[r]	Mo[r]			Mo	Nb or TZM					
Coolant			H_2O; Li			Li_2BeF_4	Li_2BeF_4			Li_2BeF_4	Helium					Li
Primary Blanket			H_2O, Li, SS			Inor 8, LiH	Inor 8, LiH				Li, Graphite, H_2O, B					
Moderator - Reflector - Attenuator			H_2O, Li, SS			H_2O, Pb, B	H_2O, Pb, B				Li, Graphite, H_2O, B					
Gamma Shield						Pb	Pb									
Power Density:																
Vacuum Wall	p_w	kW/liter	138			~143	~143									
Coolant	p_c	kW/liter				10.4	10.4									
Primary Blanket	p_p	kW/liter	300[s]			0.13 (max 39)	0.13 (max 39)									
Moderator-Reflector-Attenuator	p_m	kW/liter				0.078	0.078									
Gamma Shield	p_g	kW/liter				0.0036	0.0036									
Temperatures:																
Vacuum Wall	T_w	°C	H_2O; Li			1000	1000				1000					
Coolant	T_c	°C	350(H_2O); 1000(Li)			774 - 834	774 - 834									
Primary Blanket	T_p	°C				834 - 894	834 - 894									
Moderator - Reflector - Attenuator	T_m	°C				324	324									
Gamma Shield	T_g	°C				324	324									
Total Blanket Thickness		m			1.2	1.25	1.25									
Total Shield Thickness		m														

TABLE I REACTOR PARAMETERS FOR CLOSED SYSTEMS (Contd.)

			Stellarators		Tokamaks					Toroidal Machines					θ-Pinch
			Spitzer et al.[2]	Gibson[3]	Golovin et al.[4]	Carruthers et al.[5,6]		Butt[8] Simple Model	Gibson[3]	Mills[9]	Förster & Schneider[10]	Butt[8] Simple Model	James, Newton, Bodin[11,12]		Burnett & Ellis[13]
						α-Heating	Injection						Resistive[b]	Supercond[b]	
PRIMARY COOLANT SYSTEM															
Coolant			H_2O Li							Li_2BeF_4	Helium				
Total Flow Rate	Q	kg/sec	9.3(10[10])	7.1(10[9])							2209 kg/sec				
Reactor Flow Rate	Q_r	kg/sec													
Bypass Flow Rate	Q_b	kg/sec													
Total Pressure Drop	Δp_h	psi													
Hydraulic	Δp_h	psi													
Electromagnetic	Δp_{em}	psi													
Pumping Power	P_p	MW													
Hydraulic	P_h	MW	110												
Electromagnetic	P_{em}	MW													
Temperatures															
Blanket Inlet	T_{bi}	°C	290			774	774				518				
Outlet	T_{bo}	°C	334			894	894				950				
Heat Exchanger Inlet	T_{xi}	°C													
Outlet	T_{xo}	°C	482												
Turbine Outlet	T_{to}	°C									553				
Compressor Inlet	T_{ci}	°C									32				
Compressor Outlet	T_{co}	°C									93				
Pressure															
Reactor Outlet		Bar									90				
DIRECT-CONVERSION SYSTEM															
FUELING SYSTEM															
Mode of Injection			Neutral gas and/or liquid globule[t]				Heated Plasma								Gas Flow
Injector Beam Energy	V_b	keV													
Injector Beam Current	I_b	A													
Injector Beam Power to Plasma	P_b	MW													
Injector Input Power	P_I	MW					147[u]								
Fuel Input	D_2	kg/day	81			12.3	<4.3								
	T_2	kg/day	122			18.5	<6.5								
Fuel Consumption	D_2	kg/day	1.4			0.43	0.43			0.94					
	T_2	kg/day	2.1			0.65	0.65			1.41					
(Nat. Li) ^6Li		kg/day				(0.15) 1.35				2.82					
Fractional Burnup			0.0176			0.035	>0.10			0.027					0.032
FUEL RECOVERY & BY-PRODUCT REMOVAL SYSTEM															
Helium Production		kg/day								3.76					
Tritium Production		kg/day													
Vacuum Throughput		moles/sec	0.465							0.2					
Pumping Speed		liters/sec	7.95(10[6])							0.68(10[6])					
Pressure in Divertors		mTorr	1							5					
Number of Diffusion Pumps			265												
Booster Pumps			265												
Mechanical Pumps			100												

FOOTNOTES

[a]Calculated by us.

[b]Parameters listed for Cycle No. 2 with no reheat.

[c]Includes neutronic radiation, charged particles, and magnetic field dissipation.

[d]Vacuum wall radius of straight section, r_w.

[e]Dimensions pertain to stellarators and nontorus systems.

[f]Total axial length, i.e., straight section and curved sections.

[g]Based on Homeyer's blanket design.[7]

[h]Compositions: 50% D, 50% T (or as indicated).

[i]Calculated, using q = 1 and aspect ratio A = 3.5.

[j]Calculated, using L_C/L_D = 0.2.

[k]Obtained from Fig. 5 of Ref. 12.

[k]Obtained from Fig. 5 of Ref. 12.

[l]Ohmic heating of plasma to 10^6 °K, with magnetic pumping to final temperature, 10^8 °K (Ref. 15).

[m]Required effective plasma resistance during plasma-current rise time.

[n]Calculated from $q = B_T/AB_p$.

[p]Vacuum wall loading P_w, defined as P_f/vacuum-tube surface area.

[q]Actual heat load on divertor wall from bremsstrahlung radiation and charged particle impact.

[r]Blanket design of Homeyer[7] and Impink.[14]

[s]Near blanket inner radius where power density peaks, total heat generation in coolant (water) flowing through pipes.

[t]Injection systems were proposed, with recommendation that experiments be performed to study these systems.

[u]Based on 7% efficiency of thermal power at 42% station efficiency.

wall loading of P_W = 13 MW/m^2 from the engineering review papers of Carruthers et al.[5,6] The results for a 5000-MWt reactor are presented in Table I. This very large size is considered by Golovin et al. to be the smallest economically feasible size for tokamak systems.

Golovin et al. also include parameters for two intermediate experimental units, which they consider as necessary steps before the industrial-scale 5000-MWt unit can be completely designed. These are not included in the present survey. The first of these facilities is a small 50-MWt laboratory unit with a wall thermal loading of 1.3 MW/m^2. This unit does not include a blanket, and magnetic fields are generated with uncooled copper coils next to the vacuum wall. The maximum toroidal magnetic field of 60 kG is anticipated for this design.

The intermediate or "final" laboratory unit suggested has a power rating of 1500 MWt, and a vacuum wall thermal loading of 13 MW/m^2 as assumed for the industrial unit. A superconducting coil system generating a maximum field of 100 kG replaces the copper coils. The facility is designed without a tritium breeding blanket and without shielding of the coil system from neutron and gamma radiation.

2. Carruthers et al.[5,6] have surveyed the major systems of plasma confinement and examined the engineering problems and costs of a power-generating fusion reactor. The model chosen for the analysis is a steady-state toroidal geometry system containing a plasma of 50% deuterium and 50% tritium. The design parameters are listed in Table I for two different plasma heating techniques: charged-particle heating and injection of heated plasma. The two systems are tabulated under the tokamak-type reactors because of the low β's, 0.075 and 0.43, usually associated with tokamaks. The table lists an assumed gross electrical output efficiency of 0.46 for the injection-heated reactor. It is not clear whether the 7% circulating power for injection heating used in the study includes the efficiency of thermal conversion.

Their study compares the plasma parameters for a charged-particle-heated D-D reactor with the D-T system. The D-D reactor uses a sodium-blanket system.

3. Butt[8] presents the results of feasibility studies of pulsed toroidal reactors. The technological problems associated with these systems is not discussed, but the plasma parameters required for the different variants of the pulsed reactors are explored using currently accepted technical parameters. Butt points out that although the margins of stability, q, for tokamak and zeta-type reactors differ widely, the experiments in tokamak T-3 and zeta have given indications of good confinement. Therefore, the object of the study was to assess the feasibility of each type by using model plasma configurations that approximate as closely as possible

the available experimental results. The preliminary reactor parameters from the simple-model approach are presented in Table I for a tokamak reactor. The simple-model approximation assumes that the plasma pressure and current density are constant out to the plasma radius that is less than the radius of the vacuum wall. The parameters for a zeta-type reactor are listed under Toroidal Machines.

A comparison is also made for tokamak-reactor parameters using other distributions for pressure and density. The comparison shows that for a given $q = 1.3$, the more complex the model, the less feasible becomes the tokamak as a reactor, because of the required high axial magnetic fields. Butt's study includes a comparison of the simple model and experimental results for the zeta-type reactor.

4. The two representative tokamak systems selected by Gibson et al.[3] are units having a total power output of 4200 and 1650 MWe. The parameters associated with the 1650 MWe system are included in Table I. Significant parameters for this unit are: $\beta = 0.045$, $B = 110$ kG, and $P_W = 7$ MW/m^2. By way of comparison, the 4200-MWe unit involves an average $\beta = 0.005$, $B = 430$ kG, and $P_W = 22$ MW/m^2.

C. Toroidal Machines

1. Mills[9] considers the major features of a thermonuclear reactor: the plasma, vacuum field, diverter, vacuum wall, coolant, blanket, and coils. Plasma conditions and processes are discussed in some detail. The other design areas of importance listed above have their associated problems outlined, but are not covered in the same detail as the plasma. The economics are covered in sufficient depth to allow a broad cost estimate of a certain model with a tabular presentation of capital costs. Power costs of the fusion power plant are compared with the Oyster Creek coal and nuclear plants.

2. Förster and Schneider[10] emphasized the engineering and economic aspects of a toroidal fusion-reactor power plant, with special emphasis on the energy-conversion system. Plasma characteristics are almost totally ignored. Helium is chosen as the reactor coolant, and a closed-cycle gas turbine is used for the heat sink. The torus is designed to have eight removable segments, and consideration is given to two torus configurations. Calculations for the reactor heat exchanger and cycle components are performed for several thermodynamic and design parameters to evaluate optimum plant-layout requirements. Two cycles, with and without reheat, are considered. The cycle without reheat is studied for three cases of reactor pressure drop. The design of the torus with respect to construction (removable segments), materials, and heat-removal requirements is presented. Numerical information is presented on the choice of cycle and reactor cooling-tube diameter. For the plant considered, rough

cost estimates are made. Table I lists only the parameters for the case of intermediate reactor pressure drop without reheat.

3. In a comparison study, Bodin et al.[11] investigate a reactor design based on a high-β toroidal pinch in which the plasma is confined by combining axial and azimuthal magnetic fields. The azimuthal magnetic field is produced by a current flowing in the plasma around the major axis of the torus. Because the axial current must be induced by transformer action, the system is necessarily pulsed. Two possible pulsed operating modes are examined. One is the purely pulsed system without refueling during the pulse, where the pulse length approximates the burnup time (less than 10 sec). The other mode is the quasi-steady system with refueling during the pulse, whose duration can be many tens of seconds or more. The plasma parameters and dimensions developed in their study are based on a wall thermal loading, blanket thickness, and Lawson curves cited by Carruthers et al.[5] Bodin et al. also discuss the technological problems of the proposed operating cycle, temperature control, choice of wall material, and magnetic penetration of the blanket and vacuum wall.

In a concurrent study,[12] the above authors examine some design problems related to the field system and power-supply requirements of pulsed, closed-system fusion reactors. Large axial plasma currents must be induced in these systems in order to provide plasma heating and a portion of the confining magnetic field. The authors consider both superconducting and resistive windings and conclude that both systems appear to be feasible. Table I includes the preliminary design parameters for both of these systems.

D. Toroidal θ-pinch (Scyllac)

1. The toroidal-separated shock θ-pinch reactor design by Burnett and Ellis[13] accomplishes plasma heating in two stages using two energy-storage systems. In the first stage, the plasma ions are shock-heated to several keV; in the second stage, the plasma is raised to its final temperature by adiabatic compression. The shock-heating coil is driven by high-voltage circuits whose energy content is only a few percent of that of the total system. The multiturn copper compression coil operates near room temperature, and Burnett and Ellis estimate that the joule losses can be made up by direct energy conversion from the expansion of the high-β plasma against the magnetic field during the burning pulse. Magnetic energy is switched reversibly into the compression coil from a cryogenic magnetic store situated outside the reactor core. Burnett and Ellis propose that fueling and flushing of the plasma between burning pulses be accomplished by flowing D-T gas through the discharge chamber.

V. REACTOR PARAMETERS FOR OPEN-ENDED SYSTEMS: TABLE II

A. Mirror Machines

1. Post's early pioneering work[16] is based on thermal conversion only. Operating conditions are determined by stable zones in β-vs-B_0 parameter space bounded by a set of critical conditions, namely the "slow" Alfvén instability, the transverse instability, and threshold power-loss conditions for the mirror magnet-coil system. This study is omitted here.

Post's more recent work[17] includes three different fuel cycles with energy-conversion systems (direct and thermal) appropriate to each. The study includes the novel concept of circulating the directly converted energy of the escaping particles with high efficiency. The first fuel cycle is an optimized 60-40 D-T cycle, which has a blanket breeding ratio of 0.86 and which exploits neutron-multiplying reactions and energy-multiplying neutron-capture reactions in a Be-Na-^{6}Li-Nb blanket to achieve a substantial net power output. The second is a D-D cycle with 12% tritium reinjected from the D-D reaction and nonbreeding energy-multiplying, neutron-capture reactions in the Be-Na-Nb blanket. The third is an 80-20 D-^{3}He cycle with reinjected ^{3}He, direct conversion, and thermal conversion in a nonbreeding blanket.

2. The mirror-reactor design studies described by Werner et al.[18] use the concept of direct conversion of charged-particle energy into electrical power. The systems considered include Yin-Yang and axially symmetric coil configurations, with D-T and D-^{3}He fuel cycles. Direct conversion is proposed to optimize the power balance in mirror systems and to gain overall high plant efficiencies. Parametric curves are developed for an economic comparison for a variety of operating power levels, fuel cycles, and magnet systems. Werner et al. find that the D-T system with direct conversion has an economic advantage over the D-^{3}He system. However, the overall system efficiencies for D-^{3}He fueled reactors are potentially much greater than the efficiencies of reactors designed for D-T fuel cycles.

Detailed engineering and economic parameters are developed for the D-^{3}He system, and these are listed in Table II. The magnet-system parameters are obtained from the study of Moir and Taylor.[19]

3. The Fraas[20] design is strongly engineering-oriented and is based on plasma parameters from Rose.[21] This design exploits the high-temperature capability of fusion reactors by using a potassium-steam binary vapor cycle with an inlet temperature of 1000°C to the potassium turbine. Refrigeration power requirements for the superconducting magnet system are taken from a recent estimate by Fraas.[22] Much consideration is given to hazards and the broader aspects of energy requirements of the

TABLE II REACTOR PARAMETERS FOR OPEN-ENDED SYSTEMS

			Mirrors											Astron		θ-Pinch	Continuous Flow Pinch	Long Cusp
			Post[16]			Werner et al[18] Moir & Taylor[19]	Fraas[20] Rose[21]	Sweetman[25]	Cordey et al.[26]		Carruthers[27]	Werner[28]	Golovin et al.[29]	Christofilos[30]	Werner et al.[31]	Bell et al.[32]	Newton[33]	Spalding[34]
WER																		
Reactor Output Power	P	MW				5047	5000	2635[a]	2964[a]	9470[a]	1430[a]	10000	≤960[d]	11200	12000	61800[a]	10000	75000[a]
Gross Electrical Power	P_g	MWe				4704	2800	1813[a]	1960	8460	570[a]	5000	200	6950[a]	6000	26400[a]	~4000	25000
Net Electrical Power	P_e	MWe				1000		730[a]	1000	1000	355[a]			5600		5000		16300[a]
Station Efficiency	$\eta_s = P_e/P$					0.20		0.28[a]	0.34[a]	0.11[a]	0.25[a]			0.50		0.08[a]		0.22[a]
Fractional Circulating Power	$\epsilon = (P_g - P_e)/P_g$		0.62	0.72	0.70	0.79		0.60[a]	0.50[a]	0.88[a]	0.38[a]			0.19		0.81[a]		0.35[a]
$Q' = \frac{\text{Reactor Output Power}}{\text{Circulating Power}}$	$Q' = P/(P_g - P_e)$		2.4	1.9	1.7	1.37		2.43[a]	3.09[a]	1.27[a]	6.67[a]			8.3		2.89[a]	2	8.6
Fusion Pulse Power	P_p	MWt														$666(10^3)$		$1200(10^3)$
Pulse Width	t_w	sec														0.025		0.1
Pulse Period	t_p	sec														0.44		1.5
NERGY CONVERSION																		
Fusion Reaction Type[b]			$D(T,n)^4He$	$D(D,n)^3He$	$D(^3He,p)^4He$	$D(^3He,p)^4He$	$D(T,n)^4He$	$D(T,n)^4He$	$D(T,n)^4He$	$D(^3He,p)^4He$	$D(T,n)^4He$	$D(T,n)^4He$	$D(T,n)^4He$	$D(T,n)^4He$	$D(T,n)^4He$	$D(T,n)^4He$	$D(T,n)^4He$	$D(T,n)^4He$
Plasma Formation & Heating Input Power		MWe				3505		975[a]	873	6700	215			1000		21,400[a]		
Auxiliary Plasma Heating		MWe				0								0				
Alpha Particle Heating Power		MWt				0								1500				
Thermal Conversion Output Power[c]		MWe	X	X	X	188[n]	2800	697[a]	880	70	570[a]	5000		5600		23,600[a]		
Charged Particle Direct Conversion Power		MWe	X	X	X			1116[a]	1080	8390				1350				
Plasma – Magnetic Field Interaction Power		MWe														2800		
Power Conversion System Type							Potassium, Steam	Direct, Steam[d]			Steam[d]	Potassium, Steam		Direct, Steam		Steam[d]		
REACTOR DIMENSIONS																		
Vacuum Wall Length	ℓ_w	m					20	10	22.5	49.3	~10	25	7[d]		11.2	376	100	~2900
Vacuum Wall Radius	r_w	m	1[d]				2.5–5.0	2	3.96	8.7	1.75	2.2[e]	1[d]		2.8[e]	0.20	4	0.6
Blanket Length	ℓ_b	m			No Blanket		~25					25			13.2	~376		~2900
Blanket Outside Radius	r_b	m	2[d]			3.9	7.1				~3.0[d]	4.2			5.5	1.63		~1.75
Magnetic Coil Length	ℓ_m	m					~20[d]								22.7	~376		~2900
Magnetic Coil Outside Radius	r_m	m					7.4				3.50				~6.5	0.23		~2.5[d]
PLASMA PARAMETERS																		
Composition (Initial)[b]			0.6D-0.4T	0.88D-0.12T	$0.8D\text{-}0.2^3He$[k]	$D\text{-}^3He$	D-T	D-T	D-T	$0.8D\text{-}0.2^3He$	D-T	D-T	D-T	D-T	D-T	D-T	D-T[f]	D-T
Ion Density (Initial)	n	cm^{-3}				$1.23(10^{14})$	$1.75(10^{14})$	$2.1(10^{14})$	$1.4(10^{14})$	10^{14}	$3.6(10^{14})$[a]	$\le 10^{15}$	$2.5(10^{14})$	$2.1(10^{15})$	10^{15}	$2.4(10^{16})$	10^{17}	$\sim 10^{16}$
Particle Confinement Time	τ	sec						0.13			0.58			0.072		0.025	0.001	0.096
Confinement Time / Bohm Time	α						134				~90			130				
Lawson Number	$n\tau$	$cm^{-3}sec$						$2.7(10^{13})$[a]			$2.1(10^{14})$			$1.5(10^{14})$[a]		$6.1(10^{14})$	$1(10^{14})$	$1(10^{15})$
Ion Temperature	T_i	keV	300	400	400	480	15	150	100	500	15	60	~100	20	20	10	10	12
Electron Temperature	T_e	keV	50	50	50		15					20		20	20	10[d]		
β (Plasma Pressure/ Magnetic Pressure)	β					0.8	0.38	0.3 – 0.4	0.83	0.78	0.04		0.64	0.35		1		1
Length	ℓ_p	m					20	10	22.5	49.3		25	7	2.5	5.0	376	100	2900
Radius	a	m	1			2.9[a]	~4[d]	1.41[a]	2.8	6.16	1.25	1.15	0.8	1.24	1.75	0.01	0.01	0.01
Volume	V_p	liter					980,000[a]	62,800[a]				100,000[a]	14,100[a]	12,000[a]		11,800	3140	90,000
Fusion Power Density	p_f	MW/liter					0.005[a]	0.27	0.16	0.0017		0.1	0.0425[a]	0.625[a]		3.42	3.18	0.83[a]
MAGNET SYSTEM																		
Class (Material, Operating Temperature °K)						Supercond.												Supercond.
Central Axial Field	B_o	kG	15[a]			70[ℓ]		52			100	60	21-35[a]	100	70	141	300	100
Mirror Field	B_m	kG	50			140[ℓ]		200	160	180			105		84			600
Mirror Ratio			3.3	3.3	3.3	2[ℓ]		5	6.6[0]	3.8[0]			3-5		1.2			6
Inside Radius of Coil-Cryostat Assembly	r_{ci}	m	2			3.9	7.1				~3.0	4.2			5.5			~1.75
Outside Radius of Coil-Cryostat Assembly	r_{co}	m					7.4				3.5				~6.5[d]			~2.5
Length of Coil-Cryostat Assembly	ℓ_c	m					~20					25			22.7			~2900
Coil Power Dissipation	P_c	MW													0.015[l]			
Refrigeration Power	P_r	MW					~1.0[a,p]											
Total Magnet Power	P_m	MW																

TABLE II REACTOR PARAMETERS FOR OPEN-ENDED SYSTEMS (Contd.)

			Mirrors											Astron		θ-Pinch	Continuous Flow Pinch	Long Cusp
			Post[16]			Werner et al[18] Moir & Taylor[19]	Fraas[20] Rose[21]	Sweetman[25]	Cordey et al.[26]		Carruthers[27]	Werner[28]	Golovin et al.[29]	Christofilos[30]	Werner et al.[31]	Bell et al.[32]	Newton[33]	Spalding[34]
BLANKET SYSTEM																		
Vacuum Wall Loading	P_w	MW/m^2			NO BLANKET		10	13			13	30	13		68^a		0.13	0.055^m
Materials:																		
Vacuum Wall				Niobium			Niobium					Niobium, S.S.		Nb^e	Nb^e	Zr, Cu		Molybdenum
Coolant			Na, Li	Na			Lithium					.95 Li, .05 Nb		Li	Li	He, Li		Li_2BeF_4
Primary Blanket			Na, Nb, Be, B	Na, Nb, Be, B			Lithium					.95 Li, .05 Nb		Li, Nb	Li, Nb	Li, TZM, Zr		Li_2BeF_4
Moderator - Reflector - Attenuator			Na, Nb, Be, B	Na, Nb, Be, B			Graphite					.95 Li, .05 Nb		Li, Na, Be, Nb	Li, Na, Be, Nb			Li_2BeF_4
Gamma Shield							Borated H_2O, Lead							H_2O, Pb	H_2O, Pb			H_2O, Pb
Power Density:																		
Vacuum Wall	P_w	kW/liter										3000^e			0.82^e			
Coolant	P_c	kW/liter													$\sim 0.19^d$			
Primary Blanket	P_p	kW/liter													$\sim 0.23^d$			
Moderator-Reflector-Attenuator	P_m	kW/liter													$\sim 0.1^d$			
Gamma Shield	P_g	kW/liter													$\sim 0.016^a$			
Temperature:																		
Vacuum Wall	T_w	°C					1050					100^e			~875	~540		
Coolant	T_c	°C					1050								~875	~360		~500-600
Primary Blanket	T_p	°C													~875			
Moderator-Reflector-Attenuator	T_m	°C										875			~800			
Gamma Shield	T_g	°C													175			
Total Blanket Thickness		m	1	1			1.02						1.2		1.0	1.40		1.13
Total Shield Thickness		m					.97								1.0			
Breeding Ratio			0.86	0	0											1.23		
PRIMARY COOLANT SYSTEM																		
Coolant							Lithium					Lithium			$Lithium^g$	Helium		Li_2BeF_4
Flow Rate	Q	kg/sec										3210			11700			
Pressure Drop	ΔP_h	psi										50			32.6^j	86.3		
Pumping Power	P_p	MW										12.5			3.3^j	2150		
Temperatures:																		
Blanket Inlet							1000					725			$\sim 725^d$			~500
Blanket Outlet							1050					875			$\sim 925^d$			~600
Heat Exchanger Inlet												725						
Heat Exchanger Outlet												825						
DIRECT-CONVERSION SYSTEM																		
Type			Chgd. Particles	Chgd. Particles	Chgd. Particles	Chgd. Particles	None	Chgd. Particles			None	None	Chgd. Particles	Chgd. Particles	None	Magnetic Field Interaction	None	None
Expander Radius	r_e	m	100			66							50-100					
Expander Height	h_e	m	1															
Collector Outer Radius	C_{or}	m	~150															
Collector Height	C_h	m	0.5															
Expander - Collector Magnetic Field	B_e	kG	0.5			70												
Efficiency	η_D		0.9	0.9	0.9	0.96		0.9	0.9	0.9				0.90				
Output Power	P_D	MW				4218		2	1080	8390				1350		2800		
Output Potential	V_D	kV	$\sim 150^d$															
FUELING SYSTEM																		
Mode of Injection													Injection	Pellets				Gas Feed
Injector Beam Energy	V_B	keV				480		100	100	500			100	$4(10^6)^h$				
Injector Beam Current	I_B	kA				3.5^a		9.75^a	8.73	13.4			3.6	$0.25(10^{-3})^h$				
Injector Beam Power to Plasma	P_i	MWe				1680		975^a	873	6700			360^a	1000^h				
Injector Input Power	P_I	MWe				1765		1085^a	970	7444				1350^h	900			
Fuel Input	D_2	kg/day																
	$T_2(^3He)$	kg/day																
Fuel Consumption	D_2	kg/day																
	$T_2(^3He)$	kg/day																
	^6Li	kg/day																
Fractional Burnup																		
Flow Compression Ratio																	$>10^4$	
Plasma Flow Speed/Thermal Speed																	<0.1	
Plasma Current	I	kA															1500	
Plasma Potential	V_p	kV															6	
FUEL RECOVERY & BY-PRODUCT REMOVAL SYSTEM																		
Mode																		
Helium Production:		kg/day																
Tritium Production:		kg/day																
Vacuum System Throughput		moles/sec																
Vacuum System Pumping Speed		liters/sec																

TABLE II REACTOR PARAMETERS FOR OPEN-ENDED SYSTEMS (Contd.)

FOOTNOTES

[a]Calculated by us.

[b]Composition: 50% D, 50% T (or as indicated).

[c]Includes neutrons, radiation, charged particles, and magnetic field dissipation.

[d]Inferred by us.

[e]Blanket inner wall; vacuum-wall outside blanket.

[f]Initial (noncompressed) density = 10^{13} cm^{-3}.

[g]Case 3, Table VII, Ref. 31.

[h]Parameters for proton E-layer beam.

[i]Neutron flux heat deposition only.

[j]Insulated ducts assumed.

[k]^{3}He reinjected (no external source).

[l]Quadrupole magnetic well (Yin-Yang coils).

[m]Time average.

[n]Does not include 298 MWe converted from direct-conversion system losses.

[o]For vacuum fields.

[p]See Ref. 22.

future, including urban siting. The afterheat power has recently been considered anew by Dudziak[23] and Steiner,[24] who show that it is about 7% of the rated fusion power of the reactor, approximately 10^4 times the original estimate in Ref. 20.

4. Sweetman[25] emphasizes the power handled by the various components of a mirror system as a function of their respective efficiencies and shows that a major limitation on such systems is the large circulating power required for injection because of fast classical scattering into the loss cones. Two principal ways of reducing this circulating power are considered, namely, high efficiency of the total injection system (including direct conversion) and mirror ratios as large as ~5. The latter involves increasing β to ~0.5 without introducing unmanageable instabilities, maintaining adiabaticity of the confined particles, keeping radial electric fields within stability limits in both simple mirror and minimum-B systems, and staying within economic limitations. The major assumptions for the reactor design are $\beta \approx 0.4$, mirror ratio ≈ 5, and mirror field = 200 kG.

5. Cordey _et al._[26] study the economics of mirror reactors with respect to the mirror ratio, mirror magnetic fields, injection energies, and highly efficient circulating-power systems. The basic system incorporates Post's[17] technique of direct conversion of the escaping charged particles. The parameter studies include minimum-B and simple mirror systems for both D-T and D-^{3}He fuel cycles. For the current survey, Table II lists the power parameters for only two of the mirror systems. Cordey _et al._ conclude that economic factors are affected by the mirror ratio, the value of β_{max}, and the value of Q. The costs are found to be less sensitive to the maximum mirror field and the assumed maximum wall loading.

6. The Carruthers[27] design appears to have been developed mainly to establish overall size of an open-ended reactor and illustrate the magnitude of some of the more serious technological problems such as the establishment of the plasma, the injection of fuel, the extraction of ash and unburnt fuel, and the effects of interactions between the plasma and the vacuum wall. The values in the power section of the tables for this design are based on 10-m length, 1.75-m vacuum-wall radius, 13-MW/m^2 wall-flux loading, 40% thermal efficiency, and 15% fusion power required for plasma heating, all as given by Carruthers.

7. Werner[28] introduces a novel blanket design in which modular arrays of radially acting heat pipes are placed nearest the plasma, followed by a modular blanket structure surrounded outside by the vacuum wall. Consequently, the fluxes of radiant energy and charged particles are absorbed and the neutron flux is highly attenuated before reaching the vacuum wall, thereby greatly reducing the operating temperature of the latter. This design allows the wall loading on the inner-heat-pipe surface of the blanket to be taken as 30 MW/m^2, more than twice that of any other design.

8. Golovin's[29] design of a mirror fusion reactor is carried out as a comparative study with a tokamak reactor. The need for such a comparison was motivated by the undesirable aspects of the large minimum size established earlier by Golovin et al.[4] for tokamaks (output power $\gtrsim$ 5000 MWt) and the desirable aspects of a potentially smaller minimum size (output power = 600 MWt in this case) for mirror reactors using direct conversion. Meaningful comparability of the two designs is established by using the same maximum magnetic field (100 kG), the same neutron-moderating blanket thickness (120 cm), and comparable plasma densities (2.5-3.0×10^{14} cm^{-3}) in both cases. The major differences are in the plasma confinement times ($\tau_{mirror} \approx 0.1\ \tau_{tokamak}$) and plasma temperatures ($T_{mirror} \approx 10\ T_{tokamak}$). Assumptions made for the mirror plasma are that microinstabilities can be suppressed with feedback stabilization and that static multipole potential-well stabilization is not necessary. No detailed account of the power-balance parameters is given.

B. Astron

1. Christofilos[30] considers an astron with an E layer maintained by relativistic protons having 4 GeV energy (3 rest-mass units). Direct conversion is used to handle the loss-cone energy flux from the ends of the reactor, and this power (1350 MWe) is used to operate an electron-ring accelerator which provides the relativistic proton beam.

2. Werner et al.[31] apply the heat-pipe, first-wall concept to the astron. From consideration of blanket neutronics and heat pipe thermal dynamics, their parameters lead to a large first-wall power loading, 68 MW/m^2. (Our calculation is based on their model, p. 459 of Ref. 31.) However, the thickness of the heat-pipe first wall is only 0.01 cm, and although this is not the vacuum wall per se, nevertheless it is subject to the surface-effect damage from plasma radiation common to all vacuum walls.

C. Linear θ-pinch (Scylla)

1. Bell, Borkenhagen, and Ribe[32] treat four cases of energy balance and two cases of net power production in $\beta = 1$ θ-pinch reactors. The major independent variables in these cases are coil size (10-, 15- and 20-cm radii) and coolants (helium and steam). The case chosen here is for a helium-cooled net power producer having a 20-cm coil radius. Special attention is given to the engineering design of the gas-cooling system, and a study is made of different coil and support structures and their effect on the tritium breeding ratio of the blanket. For those parameters in Table II that we calculated, the model used is consistent with the power-flow diagram in Ref. 1, in which the direct-conversion power is included in the gross electrical output power.

2. Of all the various fusion-reactor concepts treated here, the one that represents the greatest extrapolation from experimental results achieved to date appears to be the continuous-flow linear pinch as described by Newton.[33] Nevertheless, the concept itself has several important advantages over the more conventional closed or open-ended systems; hence the scoping-type assessment of design parameters is a significant contribution to the present survey.

3. Spalding[34] considers variations of the basic cusp configuration including the conventional spindle cusp, a long θ-pinch with cusp ends ("long cusp"), and a symmetric hybrid θ-pinch cusp. He shows that in all cases it is necessary to use a pulsed high-beta plasma. The long-cusp example included in the current survey is the version that emerges from Spalding's study as having parameters that most nearly seem to be within reach of foreseeable technology.

VI. REMARKS

The parameters in Tables I and II are presented in such a manner as to compare reactor types and identify major subsystems, some of which have as yet received only minimum attention. A cursory review of the tabulation reveals that the preliminary nature of the studies and the diversity of approaches have yielded (understandably) design conditions that, in some instances, appear to be currently unattainable. Therefore, one of the immediate needs in fusion-reactor technology is to reconcile some of the more severely conflicting design requirements and to bring interface problems into better perspective.

For example, the blanket parameters are not determined specifically for many of the reactor systems listed. The limited mechanical-design effort in the structural requirements of the blanket and superconducting-magnet system has not allowed realistic estimates on the content of structural material to be determined at this time. This will have consequences affecting the tritium breeding ratio for the $D(T,n)^4He$ fuel-cycle systems. A second example is the thermal loading and operating temperatures of the vacuum wall. In most of the studies, the values are adapted from Homeyer's estimate of 13 MW/m^2 and have not been analyzed specifically for each design. Therefore, it is not clear that these design conditions are consistent with the constraints imposed by other subsystem requirements and structural integrity.

The limited data generated in the studies thus far reported would make an evaluation of the systems and/or subsystems premature at this time. The compilation is intended to provide background material for a subsequent phase of developing a coordinated overall reactor systems-design study. Through this coordinated effort, consistent interrelationships between power balance and design constraints will be established and can lead to a more meaningful appraisal of the different thermonuclear power reactors.

It is planned to periodically update this survey to reflect the advances being made in total systems design.

REFERENCES

1. P. J. Persiani, W. C. Lipinski, and A. J. Hatch, "Power-Balance Parameters Q and ε as Measures of Performance for Fusion Power Reactors," *Proc. Texas Symposium on the Technology of Controlled Thermonuclear Fusion Experiments and the Engineering Aspects of Fusion Reactors*, November 20-22, 1972, Austin, Texas. See also *Some Comments on the Power-balance Parameters Q and ε as Measures of Performance for Fusion Power Reactors*, ANL-7932 (June 1972).

2. L. Spitzer, Jr., D. J. Grove, W. E. Johnson, L. Tonks, and W. F. Westendorp, *Problems of the Stellarator as a Useful Power Source*, NYO-6047 (1954).

3. A. Gibson, "Permissible Parameters for Economic Stellarator and Tokamak Reactors," *Proc. Conf. Nuclear Fusion Reactors*, UKAEA, British Nucl. Energy Soc., p. 233 (Sept 1969). See also: A. Gibson, R. Hancox, and R. J. Bickerton, "On the Feasibility of Stellarator and Tokamak Fusion Reactors," *Proc. IAEA 4th Conf. Plasma Physics and Controlled Nuclear Fusion Research*, Madison, Wisconsin, June 17-23, 1971, Vol. III, Paper No. IAEA/CN-28/K-4, p. 375.

4. I. N. Golovin, Yu. N. Dnestrovsky, and D. P. Kostomarov, "Tokamak as a Possible Fusion Reactor--Comparison with other CTR Devices," *Proc. Conf. Nuclear Fusion Reactors*, UKAEA, British Nucl. Energy Soc. (Sept 1969), p. 194.

5. R. Carruthers, P. A. Davenport, and J. T. D. Mitchell, *The Economic Generation of Power from Thermonuclear Fusion*, CLM-R-85 (1967).

6. R. Carruthers, "Engineering Parameters of a Fusion Reactor," Ibid. Ref. 4, p. 337.

7. W. G. Homeyer, *Thermal and Chemical Aspects of the Thermonuclear Blanket Problem*, MIT Res. Lab. Electron. TR-435 (1965).

8. E. P. Butt, "Feasibility Studies of Pulsed Toroidal Reactors," Ibid. Ref. 4, p. 268.

9. R. G. Mills, "Some Engineering Problems of Thermonuclear Reactors," *Nucl. Fusion 7*(4), 223 (1967).

10. S. Förster and K. U. Schneider, "Design Possibilities and Consequences for the Conventional Parts of Fusion Power Plants," *Proc. 6th Symp. Fusion Technol.*, Aachen, Germany, Sept 22-25, 1970, p. 445.

11. H. A. B. Bodin, T. E. James, and A. A. Newton, "A Pulsed Reactor Based on the Toroidal Pinch," Ibid. Ref. 4, p. 255.

12. T. E. James, A. A. Newton, and H. A. B. Bodin, "Some Design Aspects of the Field System and Associated Power Supply of Pulsed Toroidal Fusion Reactors," Ibid. Ref. 4, p. 282.

13. S. C. Burnett and W. R. Ellis, *Radiation and Wall Flux Calculations for a Theta-Pinch Scientific Feasibility Experiment and a Prototype Reactor*, LA-4814 (Dec 1971).

14. A. J. Impink, *Neutron Economy in Fusion Reactor Blanket Assemblies*, MIT Res. Lab. Electron. TR-434 (1965).

15. J. M. Berger, W. A. Newcomb, J. M. Dawson, E. A. Frieman, R. M. Kulsrud, and A. Lenard, "Heating of a Confined Plasma by Oscillating Electromagnetic Fields," *Proc. 1958 Geneva Conference*, Vol. 31, p. 112.

16. R. F. Post, "Critical Conditions for Self-Sustaining Reactions in Mirror Machines," *Nuclear Fusion: 1962 Supplement--Part 1*, p. 99.

17. R. F. Post, "Mirror Systems: Fuel Cycles, Loss Reduction and Energy Recovery," Ibid. Ref. 4, p. 88.

18. R. W. Werner, G. A. Carlson, J. D. Lee, R. W. Moir, R. F. Post, and C. E. Taylor, "Engineering and Economic Aspects of Mirror Machine Reactors with Direct Conversion," *Proc. IAEA 4th Conf. Plasma Physics and Controlled Nuclear Fusion Research*, Madison, Wisconsin, June 17-23, 1971, Vol. III, Paper No. IAEA/CN-28/K-2, p. 329.

19. R. W. Moir and C. E. Taylor, "Magnets for Open-Ended Fusion Reactors," *Proc. 5th Intersociety Energy Conversion Engineering Conf.*, Las Vegas, Nevada, p. 1-80 (Sept 1970).

20. A. P. Fraas, "Conceptual Design of a Fusion Power Plant to Meet the Total Energy Requirements of an Urban Complex," Ibid, Ref. 4, p. 1.

21. D. J. Rose, *On the Feasibility of Power by Nuclear Fusion*, ORNL-TM-2204, pp. 103, A-11, A-20 (1968).

22. A. P. Fraas, *Cryogenic Systems for the Superconducting Magnets of a Full-Scale Thermonuclear Power Plant*, ORNL-TM-3097 (Dec 1970).

23. D. J. Dudziak, "A Technical Note on D-T Fusion Reactor Afterheat," *Nucl. Technol. 10*(3), 391-392 (Mar 1971).

24. D. Steiner, "A Review of the ORNL Fusion Feasibility Studies," Ibid. Ref. 19, p. 29.

25. D. R. Sweetman, "Mirror Reactors: Some General Considerations," Ibid. Ref. 4, p. 112.

26. J. G. Cordey, F. B. Marcus, D. R. Sweetman, and E. J. H. Watson, "Efficient Recirculation of Power in Mirror Reactors," Ibid. Ref. 18, Paper No. IAEA/CN-28/K-3, p. 353.

27. R. Carruthers, "Engineering Parameters of a Fusion Reactor," Ibid. Ref. 4, p. 337.

28. R. W. Werner, "Module Approach to Blanket Design--A Vacuum Wall Free Blanket Using Heat Pipes," Ibid. Ref. 4, p. 536.

29. I. N. Golovin, "Mirror Reactor Feasibility Comparison with Tokamak Reactor," Ibid. Ref. 19, p. 1-1.

30. N. C. Christofilos, "Astron Plasma Parameters Confined in the Closed Magnetic Well of a Proton E-Layer," Ibid. Ref. 4, p. 173.

31. R. W. Werner, B. Meyer, P. B. Mohr, and J. D. Lee, "Preliminary Design Considerations for an Astron Power Reactor System," Ibid. Ref. 4, p. 449.

32. G. I. Bell, W. H. Borkenhagen, and F. L. Ribe, "Feasibility Studies of Pulsed, High-β Fusion Reactors," Ibid. Ref. 4, p. 242.

33. A. A. Newton, "Fusion Reactors and Plasma Flow," Ibid. Ref. 4, p. 182.

34. I. J. Spalding, *Cusp Containment and Thermonuclear Reactors*, Nucl. Fusion *8*(3), 161 (1968).